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Follow-on Studies
Using the Voyager Spacecraft Thermal Model

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The 42-year-old Voyager mission, now named the Voyager Interstellar Mission (VIM) is operating long beyond its design life. In 2012, Voyager 1 crossed the heliopause into interstellar space and Voyager 2 made the same transit in November 2018. Due to declining power output from the Radioisotope Thermoelectric Generators (RTGs) the Science and Flight Operations teams continue to make difficult choices in terms of managing both the power and thermal margins to preserve critical science observations and maintain the health of the two spacecraft. A previous paper, "Creating a Voyager Thermal Model 39 Years Into the Flight Mission, Along With Model Correlation and Application" described how a thermal model of these 1977 spacecraft was developed and correlated without many design artifacts and with limited temperature telemetry. This paper describes how the thermal model has been used to establish an Allowable Flight Temperature (AFT) limit for hydrazine propellant in the propulsion subsystem to minimize the risk of freezing. Voyager 2 temperatures have already descended to this limit in the vicinity of the Roll thruster propellant lines. The Flight Operations team has investigated several ways of detecting propellant freezing based on analysis and trending of thruster performance telemetry. In addition, the Voyager thermal model is being used to predict the spacecraft response to possible changes in power state. These changes could involve turning off outboard science instruments and/or their heaters to increase power margin and hence power dissipation inside the spacecraft bus (i.e. in Bay 7, where the power regulation electronics are located). Changes might also be made to turn on or off other loads inside the bus to more effectively heat the coldest propellant lines. Many of these changes have been or will be tested first on Voyager 1 which has more power margin and does not have the power matrix commanding issues experienced on Voyager 2.

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Nomenclature

AFT = Allowable Flight Temperature
DN = Digital Number
FLT = Flight
JPL = Jet Propulsion Laboratory
MAGROL = Magnetometer Roll
PRT = Platinum Resistance Thermometer
REV = Revolution
RSS = Root Sum Squares
RTG = Radioisotope Thermoelectric Generator
STV = System Thermal Vacuum
T/VA = Thruster/Valve Assembly

I. Introduction[1]

As the Voyager 1 and 2 spacecraft have both left the Solar System, project scientists hope to keep the remaining powered instruments on board functioning and collecting once-in-a-lifetime data for as long as possible. However, due to the decreasing power produced by the Radioisotope Thermoelectric Generators (RTGs), propellant temperatures are approaching the freezing point. Frozen propellant, particularly in the thruster feed lines, could cause loss of attitude control and potential loss of spacecraft if fault protection is unable to recover. This paper discusses how this freezing risk is assessed and managed such that the Science and Flight Operations team can make the best trade-offs between science return and maintaining the health of the spacecraft.

The project requested thermal and propulsion engineers to assess and determine a new, higher-risk, minimum Allowable Flight Temperature (AFT) (well below the original mission's AFT) and predicted propellant cooling rate as guidelines to be used in the science/engineering trades. The assessment is based on legacy Voyager documents, flight data, a Voyager thermal model[2] correlated to a limited set of flight telemetry, and lessons learned from the Ulysses extended mission[5]. This has implications for important science activities, such as Magnetometer rolls (MAGROLs) for instrument calibration, and for fault protection. Ultimately this assessment may assist the Voyager project in making decisions on the order in which science instruments are permanently turned off.

II. Overview of the Thermal Model[2]

A Voyager Thermal Desktop model was developed in 2015 and correlated to 2014 Voyager 2 flight data for hot and cold power states[2]. The comparison of the flight data to the thermal model results is shown in *Table 1*. Based on that limited telemetry, the model is accurate within ±4°C for the hot case and ± 5°C for the cold case.

Table 1. Hot and Cold Case Thermal Model Results Compared to Flight Telemetry.

			2014-343	2014-247					
			XB-LO, GYON	XB-HI, GYOFF					
			HOT CASE	COLD CASE	HOT CASE	COLD CASE	HOT CASE	COLD CASE	
VGR 2 CHNL #	VGR 2 CHNL LABEL	Description	Flight Data [°C]	Flight Data [°C]	Predictions [°C]	Predictions [°C]	Delta [°C] TMM-Flt	Delta [°C] TMM-Flt	TD Model Node Number
E-0000	BAY_1T	Bay 1 Temp	25.8	23.7	24.2	22.6	-1.6	-1.1	AVG (BAY1_RFS.17,19,27,29)
E-0001	BAY_2T	Bay 2 Temp	17.6	14.1	19.0	17.3	1.4	3.2	BAY2_DSS.79
E-0002	BAY_3T	Bay 3 Temp	15.4	11.9	18.8	16.9	3.4	5.0	BAY3_CCS.84
E-0003	BAY_4T	Bay 4 Temp	13.3	9.7	15.8	13.6	2.5	3.9	BAY4_FDS.23
E-0004	BAY_5T	Bay 5 Temp	23.4	18.5	22.9	20.7	-0.5	2.2	BAY5_HYPACE.42
E-0005	BAY_6T	Bay 6 Temp	25.4	16.9	24.1	15.9	-1.3	-1.0	BAY6_DRIRU.32
E-0006	BAY_7T	Bay 7 Temp	20.3	20.3	19.8	19.0	-0.5	-1.3	AVG (BAY7_PWR.26,28,34,36)
E-0007	BAY_8T	Bay 8 Temp	13.8	10.3	14.9	11.9	1.1	1.6	BAY8_PSU.24
E-0008	BAY_9T	Bay 9 Temp	18.0	13.8	18.6	14.5	0.6	0.7	BAY9_RFS.23
E-0009	BAY_10T	Bay 10 Temp	21.1	19.0	21.8	19.0	0.7	0.0	BAY10_MAG_MDS.43
E-0292	SURF_T1	TCAPU Surface Temp 1	20.5	14.9	18.6	18.7	-1.9	3.9	PROP_LINE1.14
E-0293	SURF_T2	TCAPU Surface Temp 2	25.0	20.1	25.6	24.6	0.6	4.5	PROP_LINE1.145
E-0294	TANK_T1	TCAPU Tank Temp 1	15.4	12.6	12.2	9.0	-3.2	-3.6	AVG (FUEL_TANK.1, 8)
E-0295	TANK_T2	TCAPU Tank Temp 2	14.8	12.7	11.0	8.0	-3.8	-4.6	AVG (FUEL_TANK.50 47)
E-0296	FEED_T1	TCAPU Feed System Temp 1	12.0	8.5	11.1	9.6	-0.9	1.1	PROP_LINE.20
E-0297	FEED_T2	TCAPU Feed System Temp 2	22.0	17.8	17.9	17.0	-4.1	-0.8	PROP_LINE1.268

The model was also assessed by Juan Villalvazo. Juan verified the model and made recommendations for model runs with Bill Ledeboer to confirm the reasonableness of the model within the limited visibility into the flight temperatures, and made model-run suggestions to bound the worst case conditions. They also confirmed that the temperature predictions are within ±5°C of flight telemetry based on the cold case.

III. Voyager Propulsion System Thruster Performance[1]

Both Voyager spacecraft are experiencing thruster degradation. The thruster degradation performance was assessed in 2017. The conclusion of this assessment was that thruster degradation was not caused by low propellant temperature or freezing.

The coldest assessed temperature in the Voyager 2 propulsion system at the time of the AFT assessment was the +Roll propellant line at 4.0°C, based on derived temperature channel E-0991 (+R Line T). Based on thruster performance, there is currently no suspected propellant freezing.

IV. PRT Sensor Telemetry Uncertainty[1]

There are four primary sources of error considered with the PRT sensor uncertainty: Sensor uncertainty (calibration), digital number quantization error, lead wire resistance bias error, PRT mounting error. There is also an error associated with the avionics current source for the PRT electronics—this is unknown, in that no one on Voyager has these details on the avionics. There is also an error associated with using derived channels.

Using drawings from Voyager, the team determined the make and part number for the PRT used on Voyager—UTC Aerospace Systems' Rosemont Aerospace, Inc division, in Burnsville, MN (formerly a division of B.F. Goodrich,). The sensor is the 0118AKT. Rosemont provided sensor uncertainty information that was folded into the overall error budget. According to the vendor, since "the sensor-specific R vs T table was programmed into the spacecraft for each individual sensor serial number, then the accuracy near 0°C will be on the order of the calibration uncertainty at 0°C. A typical value would be +/- 0.10°C." The error tends to grow with increasing/decreasing temperature (away from a calibration point), but since the measurements in question are so close to 0°C, this value is a reasonable assumption of the measurement uncertainty.

Voyager has a 0.7°C quantization per digital number (DN). So the temperature will seemingly step by 0.7°C as the temperature increases or decreases. Note that for derived channels, this value is averaged between two different sensors so it shows a 0.35°C step size.

The lead wire adds to the resistance of the total line. Without knowing the wire gages, cable routing, pins, et cetera, it is difficult to know this value precisely. However, it is a standard bias error, and a reasonable value used for missions like MSL and SMAP is ±0.2°C based on 26 gage wire, and 2-meters of stranded copper wire from source to PRT and back. We would not expect the differences in wire/cabling from 1977 to present to have changed such that this value would change much.

Errors in PRT mounting involve sensing the substrate temperature, where the bonding material acts as a thermal resistor to the actual temperature. Again, without knowing the precise method of applying PRTs to substrates for Voyager, a very standard assumption for a PRT of this type would be a ± 0.05°C error.

Table 2 contains the various contributions to errors that add to the temperature flight data uncertainty. The RSS of this data leads to an overall error of ±1.3°C.

Table 2. Error Sources in the Temperature Telemetry

Lead Wire Error	±0.2°C
Digital Number Quantization Error	0.7°C/DN
PRT Accuracy Based on Calibration Curve	±0.1°C
PRT Mounting Error	±0.05°C
Uncertainty in the J. Smith Offsets for Derived Channels (diff model results vs. derived results)	± 1.1°C

RSS Measurement Uncertainty	**$\underline{+}$ 1.3°C**

However, because there are uncertainties in the system *the authors recommended adding an additional 1°C margin* for overall uncertainties. *So the uncertainty ought to be $\underline{+}$2.6°C.* One of the two known uncertainties involve the exact freezing point of hydrazine based on its age and water content. The other known uncertainty is the error in the current source for the PRT sensors. If the current source varies, than the measured value is changing by the amount of apparent resistance change associated with that source's change. The good news is that most current sources are calibrated for either 0°C or 20°C. The error for these sources tend to grow greatly with increase/decrease in temperature from those values, and would be expected to be very small for the propellant line temperature range.

V. Spacecraft Thermal History[1]

The Figure 1 plot of Voyager 2's +Roll Propellant Line indicates that the temperature would drop below the AFT in 2018, which it did (current temperature as of March 2019 is 3.2°C)

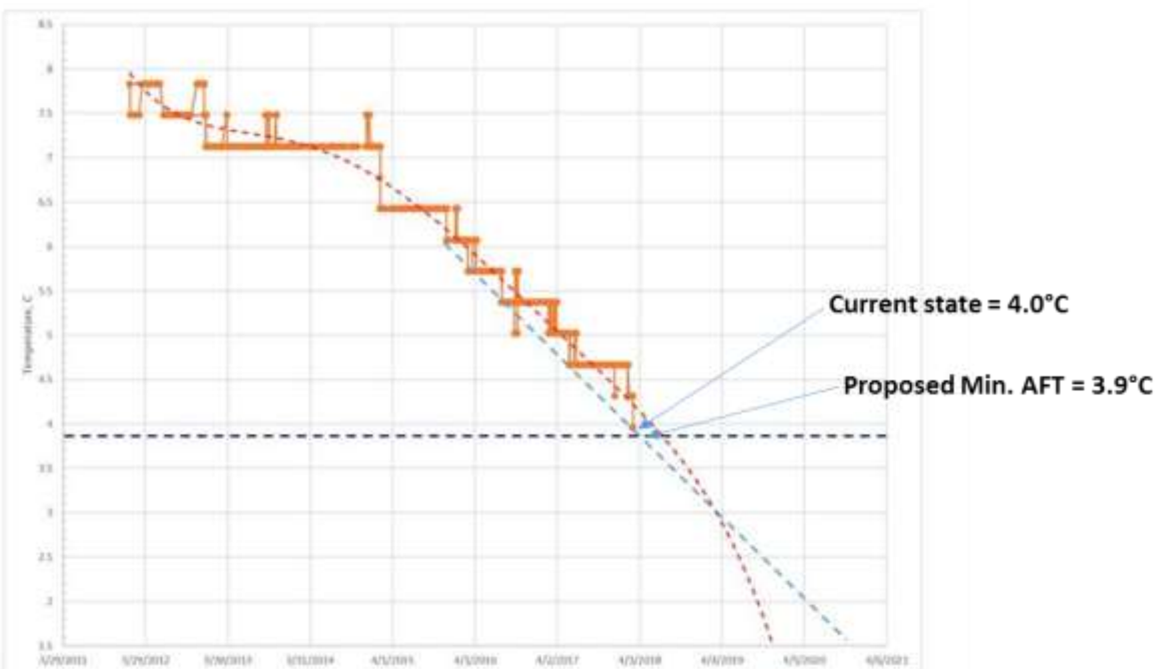

Figure 1 Post-Processed Minimum Temperatures for the +Roll Prop Line (Derived Channel)Voyager 2 ††

†† Plot produced by Fernando Peralta, Voyager Mission Operations Engineer

The minimum recorded temperature on the Voyager propellant lines occurred during a 2-REV MAGROL maneuver. During a MAGROL maneuver, power to the Bay 1 and Bay 9 heaters are turned off to make power available to perform the maneuver. A known side-effect of this power configuration is the cooling of Bays 1 and 2 while power is diverted, which also cause the +Roll propellant lines to cool since they are conductively coupled to the spacecraft bus. MAGROLs are typically performed four times per year for sensor calibration, and have been recently limited to two revolutions per maneuver maximum, with single revolution MAGROLs now possible.

During the Day 348 2017 Voyager 2 MAGROL maneuver, the propellant line temperatures dropped from 4.7°C to 3.6°C on that derived channel, a rather small decrease of 1.1°C. Yet with the uncertainties in modeling and sensor telemetry, this small change put the lines at risk of freezing. (Note, The latest MAGROL in August showed a smaller temperature drop less than 1°C could be due the coarseness of the data points.)

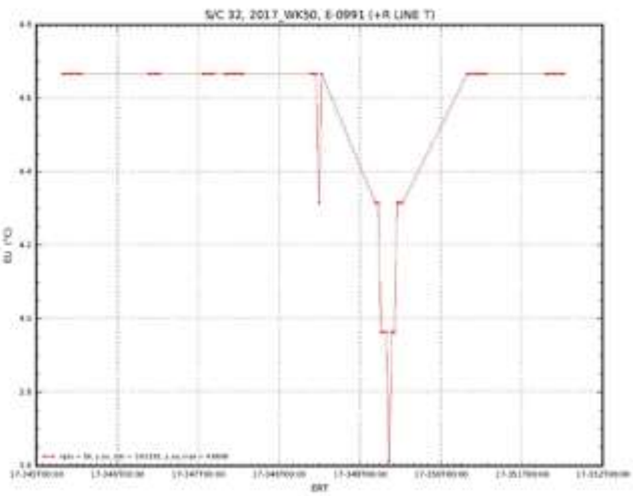

Figure 2 Voyager 2 Propulsion Minimum Recorded Temperature During 2-REV MAGROL Maneuver. The minimum temperature reached 3.6°C.

During the 16-063 anomaly propellant line temperatures dropped from 6°C to the lowest derived channel temperature of 2.9°C and stayed at that level for two days. The two graphs in Figure 3 show data from a temperature sensor on a propellant line near the tank and the estimated coldest temperature on the propellant line The temperature drop in the telemetry data has the same magnitude as the estimated temperature drop on the coldest spot on the propulsion lines. Enrique Medina has stated that attitude control subsystem did not detect any degradation of thruster performance that might indicate slushy or freezing hydrazine.

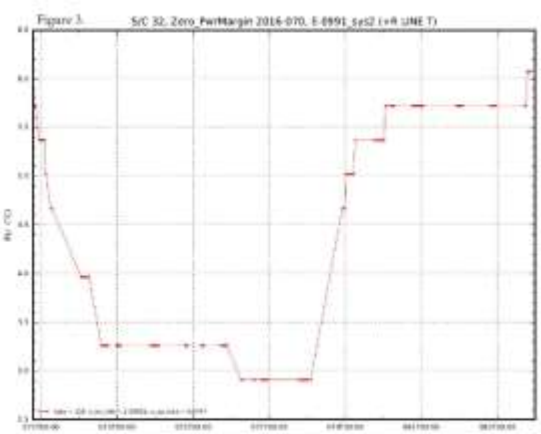

Figure 3 Voyager 2 Propulsion Minimum Recorded Temperature During 16-063 Power Margin Anomaly. The minimum temperature reached was 2.9°C for a 2-day duration. Note that quantization errors make this appear

stepwise and not smooth. The actual temperature may have thus been as low as 1.6°C, but likely no lower due to the freezing point of hydrazine.

VI. Hydrazine Minimum Temperature Limit[1]

The freezing point for Voyager's hydrazine is 1.6°C based on an early study indicating the mixture and water content. There is a range for hydrazine, and based on a report concerning the chemistry and age of hydrazine in Voyager, 1.6°C is the suggested value[2]. However, a recent rescrubbing of this number suggests a value of 1.2°C may be baselined, thanks to the likely water content in Voyager hydrazine along with a very slight depression in freezing point at tank pressures of a few hundred psia.

Hydrazine shrinks when it freezes and it expands when it melts. If it expands into the tank, it is not a problem because the tank has a gas pressurized side that will act like an accumulator. If the hydrazine melts on the downstream side of the blockage, it expands towards the valves or fittings, then when it melts it will likely move the stainless steel fittings or valves, breaking something. Likely this is a catastrophic failure.

During the T/VA qualification test[4], the thermal design verified to perform at an extreme cold condition of 4.0°C (inlet/outlet thruster valve temperature) without the propellant freezing. The thruster valve was successfully fired at these temperatures. This was the coldest the system saw during ground testing.

During flight, the current coldest temperature in the propulsion subsystem is the +Roll propellant line at 4.0°C (a derived channel). The coldest hydrazine temperature occurred during a power margin anomaly in 2016. During this anomaly the +Roll propellant line temperatures decreased to 2.9°C for two days. No propellant line or thruster issues were noted following this cold temperature excursion.

Taking the coldest reported temperature of 2.9°C and subtracting the sensor uncertainty of 1.3°C, the temperature could have been as low as 1.6°C (note it could have been colder given our unknown uncertainties).

Since hydrazine did not freeze and no degraded thruster performance detected, it confirms that the temperature was likely just above 1.6°C. Since the duration was long, it would have been expected if the freezing point had been reached, it might have frozen much of the line.

The authors proposed to set the temperature limit 2.3°C above the understood hydrazine freezing point of 1.6°C. Thus, *Therefore they recommended a propellant line Minimum risk-adjusted AFT = 3.9°C for all 11 propulsion subsystem temperature telemetry channels, measured and derived.*

VII. Detection of Frozen Propellant

If propellant were to freeze in the propulsion subsystem, two questions arise. Where is the freezing most likely to occur and how could we infer from telemetry that propellant had actually frozen.

The thermal control design of the Voyager propulsion subsystem utilizes the bus temperatures and inertia to keep it warm. In areas were the propellant lines extend away from the spacecraft bus aluminum was wrapped to allow more coupling to the Bus. This strong coupling to the bus can be seen in the hydrazine temperature behavior of telemetry channel (E-0296) during dip in temperatures that occurred during the 16-063 anomaly.

The Voyager propulsion subsystem has limited temperature telemetry data (six sensors total). Based on the Jess Smith memo[2], Voyager has implemented five derived temperature channels. Due to the limited telemetry points back in 1991 J.R. Smith used the knowledge of the strong coupling design from the bus to the propellant lines and the best test data available from Voyager System Thermal Vacuum (STV) test FLT-1 Worst Case Cold to develop a method of assessing the coldest propellant line temperatures close to the thrusters using the shear plate temperatures of adjacent bus bays.

The Voyager STV test FLT-1 Worst Case Cold test was used to facilitate propellant line thermal design verification. A total of fifteen thermocouples were placed on the lines and two additional sensors were placed on the Thruster/Valve Assembly (T/VA) brackets to characterize the propulsion subsystem. The Jess Smith method utilizes the temperature deltas from the bays to the coldest sensors on the lines and brackets to assess the coldest temperatures. The limitation of this method is that it applies to a dry propulsion subsystem and it only uses a single, warmer bus temperature profile than the current flight temperatures. Sensitivities were analyzed to investigate if the colder propellant lines temperatures affected the gradient from the bus to the brackets and propellant lines.

After evaluating the report methodology and heritage the thermal team has concluded that this is a validated method and will continue to use this method to asses coldest propellant line temperatures along with thermal model predictions. In the current baseline power state, the coldest propellant temperatures are estimated to be 3.3°C in the regions near the +Roll and –Roll thrusters on Voyager 2.

The thermal model results indicate that a changes in bay temperatures will affect the temperature gradients between the bay shear-plate and the propellant lines/brackets as shown in Table 3. These with further modeling runs can be used to determine future effects of power distribution.

Table 3 Comparison of Thermal Model Results to Telemetry (including derived channels).

	BASELINE (2017-348)			2 REV MAGROL (2017-349)			MAGROL - BASELINE		BASELINE (2018-120)			2017-348 to 2018-120		DT Change
	Model		Flight Data	Model		Flight Data	Model	Flight Data	Model		Flight Data	Model	Flight Data	
Description	**Q, W**	**T, °C**	**T, °C**	**Q, W**	**T, °C**	**T, °C**	**ΔT, K**	**ΔT, K**	**Q, W**	**T, °C**	**T, °C**	**ΔT, K**	**ΔT, K**	
Bay 1 Temp	**32.7**	24.2	25.1	**32.70**	19.6	22.2	-4.5	-2.8	**32.7**	24.16	24.4	-0.01	-0.70	
-Y Min Prop Line Temp		19.2	20.1		14.6	17.2	-4.5	-2.8		19.2	19.4	-0.01	-0.70	± 0.7
Bay 1 Heater Power	**18.6**			**0**					**18.6**					
Bay 2 Temp	**17.4**	18.3	15.5	**17.40**	15.4	14.1	-2.8	-1.4	**17.4**	18.3	14.8	-0.01	-0.70	
+R Min Prop Line Temp		8.2	4.7		6.1	3.6	-2.1	-1.1		8.2	4.0	-0.01	-0.70	± 1.1
Bay 2 DTR Repl Heater Power	**0.0**			**0**					**0.0**					
Bay 3 Temp	**24.7**	16.1	11.9	**24.70**	14.7	11.2	-1.3	-0.7	**24.7**	16.1	11.2	-0.01	-0.70	
Bay 4 Temp	**9.9**	12.6	8.3	**9.90**	12.4	8.3	-0.2	0.0	**9.9**	12.6	7.6	-0.02	-0.71	
-R Min Prop Line Temp		9.6	5.3		10.2	5.7	0.5	0.4		9.6	4.6	-0.02	-0.71	± 0.3
Bay 5 Temp	**34.1**	20.7	16.4	**34.10**	21.9	17.1	1.3	0.7	**34.1**	20.6	15.7	-0.02	-0.70	
Bay 6 Temp	**0**	15.5	12.7	**14.40**	23.2	17.6	7.8	4.9	**0**	15.4	12.0	-0.04	-0.71	
+Y Min Prop Line Temp		13.5	10.7		21.2	15.6	7.8	4.9		13.4	10.0	-0.04	-0.71	± 0.3
Bay 7 Temp	**23.62**	17.0	14.0	**30.45**	19.5	16.1	2.6	2.1	**21.62**	16.9	12.6	-0.06	-1.41	
Bay 8 Temp	**0**	14.8	8.9	**0**	13.7	8.2	-1.0	-0.7	**0**	14.7	8.2	-0.06	-0.71	
±P Min Prop Line Temp		14.2	8.7		11.8	8.0	-2.4	-0.7		14.2	8.0	-0.04	-0.71	± 0.6
Bay 9 Temp	**13.57**	19.6	14.5	**13.57**	15.9	13.8	-3.8	-0.7	**13.57**	19.6	13.8	-0.03	-0.71	
Bay 9 Heater Power	**4.8**			**0**					**4.8**					
Bay 10 Temp	**12.40**	22.3	19.0	**12.40**	18.4	17.6	-3.9	-1.4	**12.40**	22.3	18.3	-0.02	-0.71	

Based on this assessment and application of the Jess Smith method, the thermal team believes that if another power margin anomaly occurs, similar to the 16-063 anomaly, the +Roll propellant lines will reach the hydrazine freezing point temperature. Response time will be critical.

VIII. Additional Recommendations and Conclusions

Based on Ulysses extended mission contingency planning, the following considerations should be included for Voyager:

Consideration 1: Regularly check for hydrazine freezing

As part of daily/regular downlink assessment operations the Voyager team monitors propulsion system temperature telemetry and thruster performance to prevent the hydrazine from freezing.

In addition, due to the small temperature margins daily/regular thruster performance is assessed to determine if any hydrazine freezing has occurred.

If the propellant lines are near the temperature limit or if suspected freezing is identified by the thruster daily assessment, Voyager team will plan new power states (e.g. instrument turn-off sequence) to prevent freezing and/or thaw any frozen region.

Consideration 2: Prevent hydrazine from freezing

Consider turning off an instrument.

Pre-condition Bay 2 & 3 to raise temperatures in the propellant line area prior to a maneuver.

Reduce duration of maneuvers.

Consideration 3: Plan for nominal hydrazine cooling.

Determine options for shifting more power dissipation into the bus (e.g. turning off outboard electrical loads). If possible, increase power closer to or in Bays 2 and 3, near the +Roll lines.

Consideration 4: Unexpected rapid hydrazine cooling

When rapid cooling occurs due to an anomaly, contingency plans should provide for diverting available power into the bus and if necessary uses thruster firings to prevent further hydrazine cooling/freezing.

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